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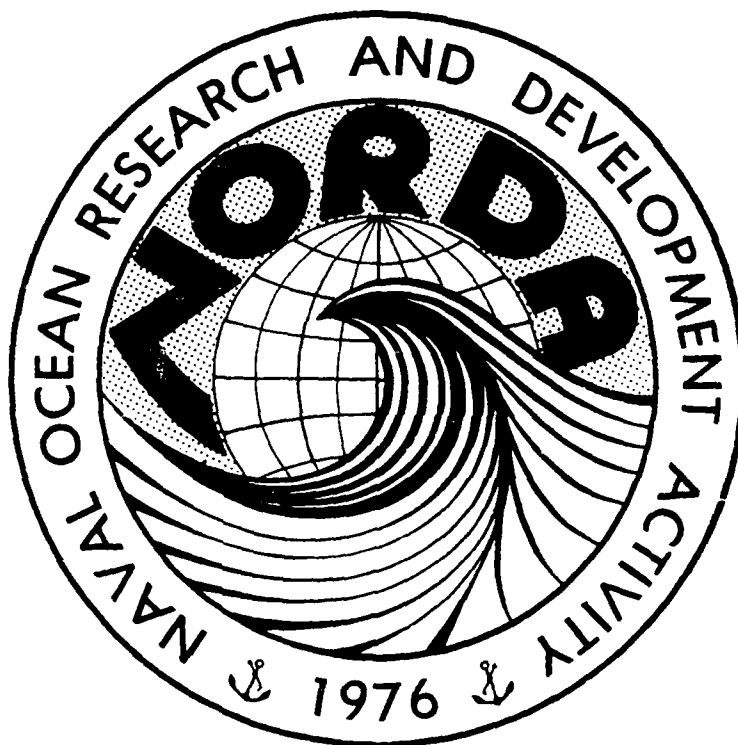
Analysis of Enclosed Internal Combustion Engine Operation with Water as the Working Fluid

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ABSTRACT

The development of a totally enclosed internal combustion engine is proposed. The engine will ingest propane, oxygen and water but no gaseous diluent. The elimination of the gaseous diluent permits the elimination of the scrubber chemicals previously required to remove the carbon dioxide produced by combustion. It is practical to liquefy the products of combustion, water vapor and carbon dioxide, and to store them as liquids if there is no gaseous diluent to be compressed during the liquefaction process.

INTRODUCTION

It is desirable to develop a totally enclosed system which contains an internal combustion engine and all the accessories required to produce at least 480 hp-hr of work. The system must perform underwater without external support and must release nothing but heat to the water.
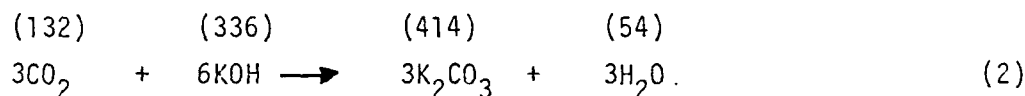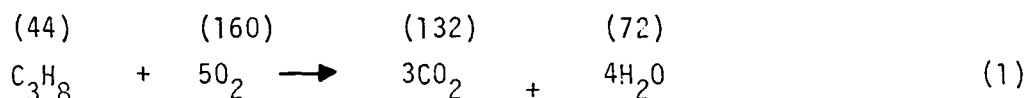
Most prior development has dealt with systems which are very similar to air breathing engines. Fuel, oxygen and a diluent gas such as nitrogen are ingested through the same kinds of intake devices used in the atmosphere. The intent is to imitate open air operation as much as possible in order to reduce hardware development. The exhaust gases are cleansed primarily of the water and carbon dioxide products of combustion and perhaps secondarily of other components such as unburned hydrocarbons, carbon monoxide and compounds produced by reactions involving the diluent. When cleansing is satisfactorily completed, fuel, oxygen and perhaps make-up diluent are added to the exhaust gas as required and the mixture is again ingested by the engine. The process is referred to as "closed cycle" engine operation. Ideally, the total pressure of the intake gases, the partial pressure of oxygen, the fuel-oxygen ratio and the ratio of the specific heats of the effective diluent should be controlled, while maintaining throttling capability, safety and reliability. The extra consumables required for treatment of the exhaust gases to guarantee a suitable ingestion gas charge represent a considerable logistics burden and add considerable weight and volume to the system. A scheme to eliminate recycling of exhaust gases would alleviate these disadvantages and eliminate many of the control variables which complicate the "closed cycle" operation.

If recycling of exhaust gases is discontinued, then either there must be sufficient diluent to process the fuel and oxygen, plus sufficient storage capacity for the used diluent and products of combustion, or else the diluent must be eliminated and only the products of combustion need to be stored. The option of choice is to eliminate the diluent. The main reasons for tolerating gaseous nitrogen as diluent in atmospheric engine operations are that it permits the "free" use of atmospheric oxygen and serves as a temperature moderator and working fluid. In closed systems, the advantage of use of normal carburetors or other readily available, reliable hardware may not be sufficient to offset all of the disadvantages of using the customary gaseous diluent. It is proposed here that a throttled engine intake system be developed to provide oxygen and propane in near shoichiometric proportions to an internal combustion engine. Liquid water will accompany the oxygen and propane and will serve as a temperature moderator and working fluid after evaporation. For an Otto cycle the oxygen, propane and water may be mixed in an intake manifold or they may be metered separately into the combustion chamber on the intake stroke.

It is necessary to include water to control the high peak combustion temperatures which would otherwise occur. However, the water vapor does not represent an additional problem in the exhaust system because water is also a product of combustion of hydrocarbons and oxygen and it is easy to

condense. Moreover, the exhaust can be dealt with downstream and separate from the engine. All of the exhaust water and carbon dioxide can be condensed and does not have to be recycled just as exhaust gases are not recycled in atmospheric operation. In effect, exhaust gas treatment and engine intake chemicals are totally and completely decoupled from each other. It may be desirable to recycle liquid water, but in contrast to gaseous diluent, there is a practical choice between recycling or storing it. It will be necessary to use some of the engine power output to condense the exhaust gases, but the sole effect on the engine will be as a mechanical load, indistinguishable from any other mechanical load, and which can be managed by throttle adjustments and adjustments to the drive train of the exhaust handling equipment. Schematicly, the inputs and outputs of the engine are shown in Figure 1.

The operational advantage of condensing carbon dioxide can be illustrated by the following two chemical reactions involving the use of propane and oxygen when potassium hydroxide is used instead of condensation to remove carbon dioxide.

$$\underset{(44)}{C_3H_8} + \underset{(160)}{5O_2} \longrightarrow \underset{(132)}{3CO_2} + \underset{(72)}{4H_2O} \qquad (1)$$

$$\underset{(132)}{3CO_2} + \underset{(336)}{6KOH} \longrightarrow \underset{(414)}{3K_2CO_3} + \underset{(54)}{3H_2O} \qquad (2)$$

The number in parentheses above each reactant or product represents the relative mass of that component involved in the reaction. For instance, the first reaction may be interpreted as a statement that 44 mass units of propane will combine with 160 units of oxygen to produce 132 units of carbon dioxide and 72 units of water. The second reaction indicates that the 132 unit of carbon dioxide from the first reaction requires 336 units of potassium hydroxide for scrubbing purposes. If sodium hydroxide is used as scrubber, 240 units are required. These massive hydroxide requirements are based on 100% utilization of the scrubber material. A more realistic requirement is 6816 pounds of potassium hydroxide solution or 1945 pounds of sodium hydroxide granules for 303 pounds of propane and 1101 pounds of oxygen to produce one mission of 480 hp-hr. (Ref. 1) The chemical scrubber weight significantly exceeds the weight of fuel and oxygen. For a multi-mission task, many tons of scrubber material would be necessary. Therefore, the elimination of the chemical scrubber would eliminate a significant supply problem as well as decrease the system turn around time and the cost of consumables. Disposal of the spent scrubber material might also be a problem that ought to be avoided.

Water and condensed carbon dioxide on the other hand would require only the work of compression for storage. The water could be safely dumped and the carbon dioxide vented to the atmosphere after the completion of a mission and the refueling of the system. The presence of a large quantity of pressurized carbon dioxide as a fire extinguisher during refueling is highly desirable. The addition of staged compression and water condensation tanks for each stage modify the proposed system as shown in Figure 2.
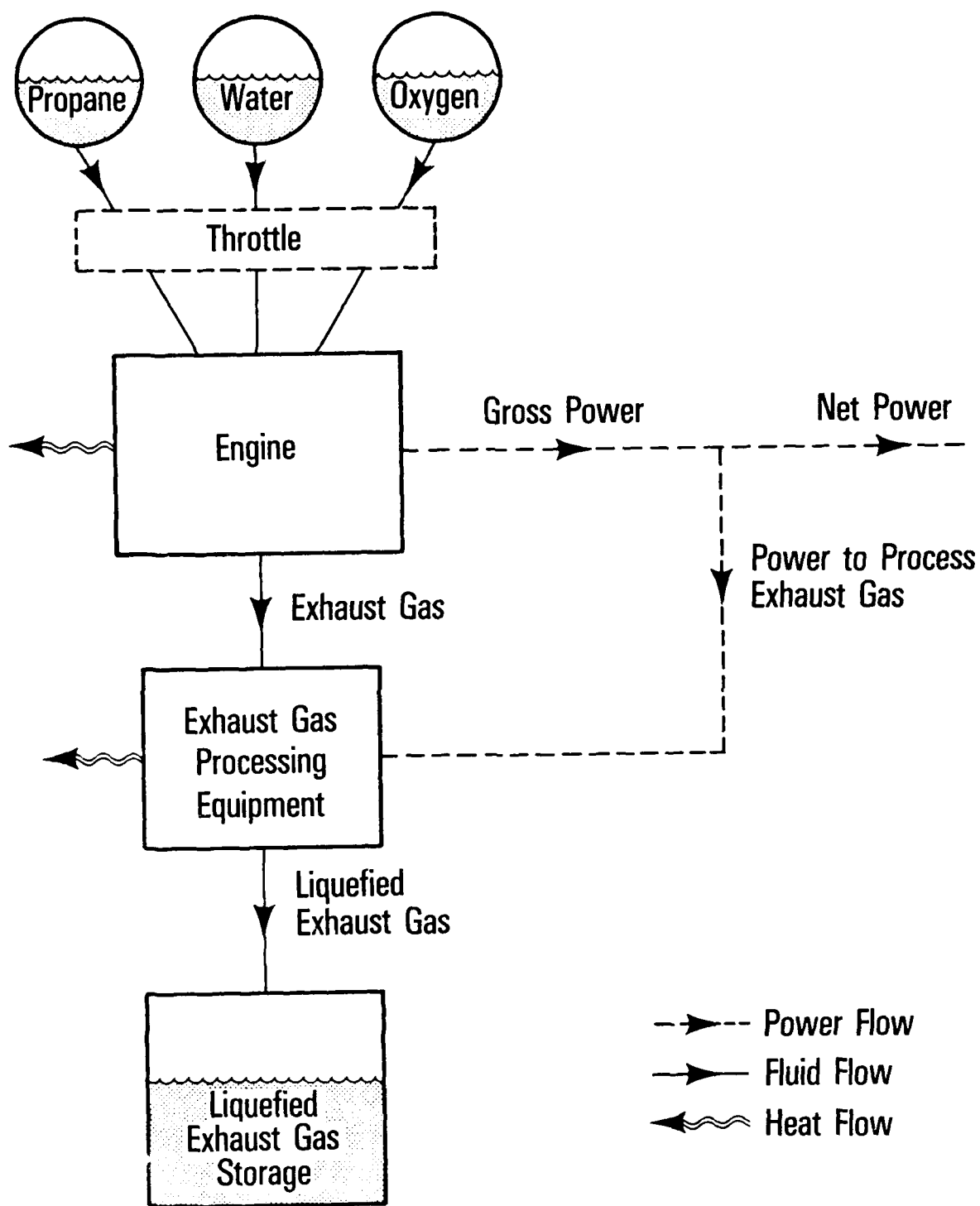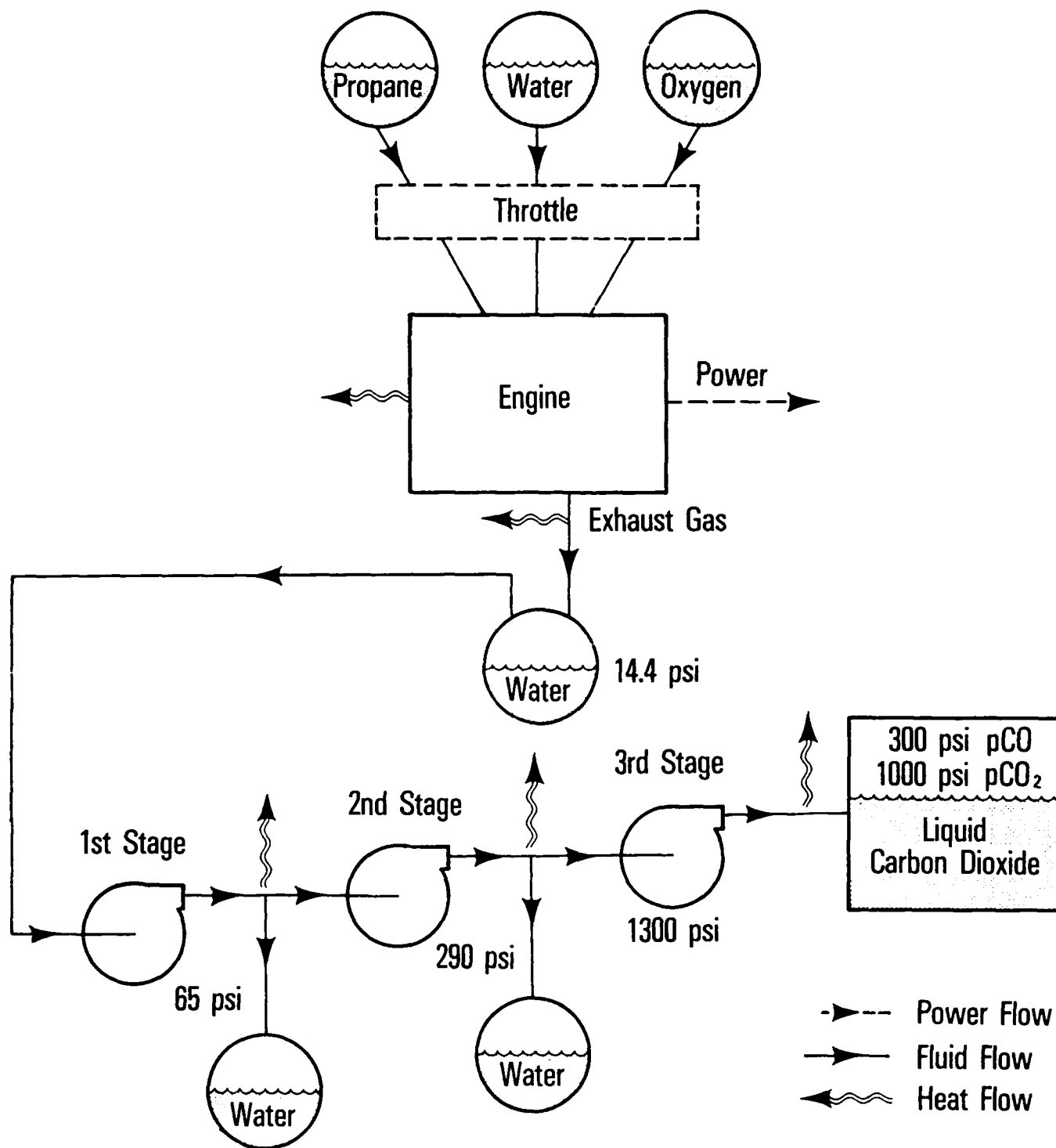
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Figure 1.

Figure 2.

The empty hardware weight of the condensed carbon dioxide system should not be greatly different from the empty weight of the chemical scrubber system. As deeper operational depths are achieved, the total system weight of each will be driven by the resistance of their pressure hulls to external pressure. Therefore, system volume will have a greater impact on system weight in the deep ocean than will the weight of the working components. On a volume basis, the condensed carbon dioxide system will probably be more desirable than the chemical scrubber system.

The preceeding has dealt with combustion products of carbon dioxide and water only. The possibility of significant amounts of impurities in the fuel and oxygen must be eliminated to prevent their accumulation in the exhaust system. In addition, unburned hydrocarbons, oxygen and carbon monoxide can be present in the exhaust gases during normal operation. They must be eliminated between the engine and the high pressure storage tank. The general goal remains to convert all consumables to either water or carbon dioxide and to store them as liquids in spite of the fact that they may temporarily appear downstream of the engine as oxygen, carbon monoxide or unburned hydrocarbons.

Of all the gases which can normally appear downstream of the engine, oxygen is the most troublesome. There is no possibility of pumping it to high enough pressure to condense it; therefore, relatively little of it can be stored downstream of the engine. It cannot easily be separated from the other gases and recycled. It could generate the risk of explosion and its metal containers can react with it. It is prudent to eliminate all of these disadvantages by eliminating oxygen in the exhaust. A catalytic converter and sufficient excess fuel to react with all available oxygen could eliminate the concerns involving oxygen.

If an excess of fuel is provided in the catalytic converter, significant amounts of unburned hydrocarbons and carbon monoxide will reach the compressor along with carbon dioxide and water vapor. Unfortunately, carbon monoxide is also non-condensable and very little can be tolerated in storage. However, when enough carbon monoxide has accumulated to be troublesome; it can be converted to carbon dioxide by recycling it through the catalytic converter and permitting it to serve as the excess fuel in the catalytic converter. Occasionally, it will be necessary to add oxygen to the catalytic converter either by direct injection or by occasionally running the engine slightly lean. Summarizing the above, it is necessary to eliminate free oxygen from the exhaust storage system by maintaining excess fuel in the catalytic converter; but to achieve this and prevent an excessive build-up of non-condensables such as carbon monoxide in the carbon dioxide storate tank, it will sometimes be necessary to add free oxygen to the catalytic converter. The two requirements are not necessarily contradictory, but there is risk of developing an unstable control system in an attempt to satisfy them. An experiment should be conducted to determine if the general goal can be achieved. The proposed catalytic converter and its control system for the purpose of finally obtaining only carbon dioxide and water from the propane and oxygen is shown schematicly in Figure 3. There exists the option to use such a rudimentory control system or to employ a more elaborate micro-processor controller with other gas sensors, pressure sensors and pumps.
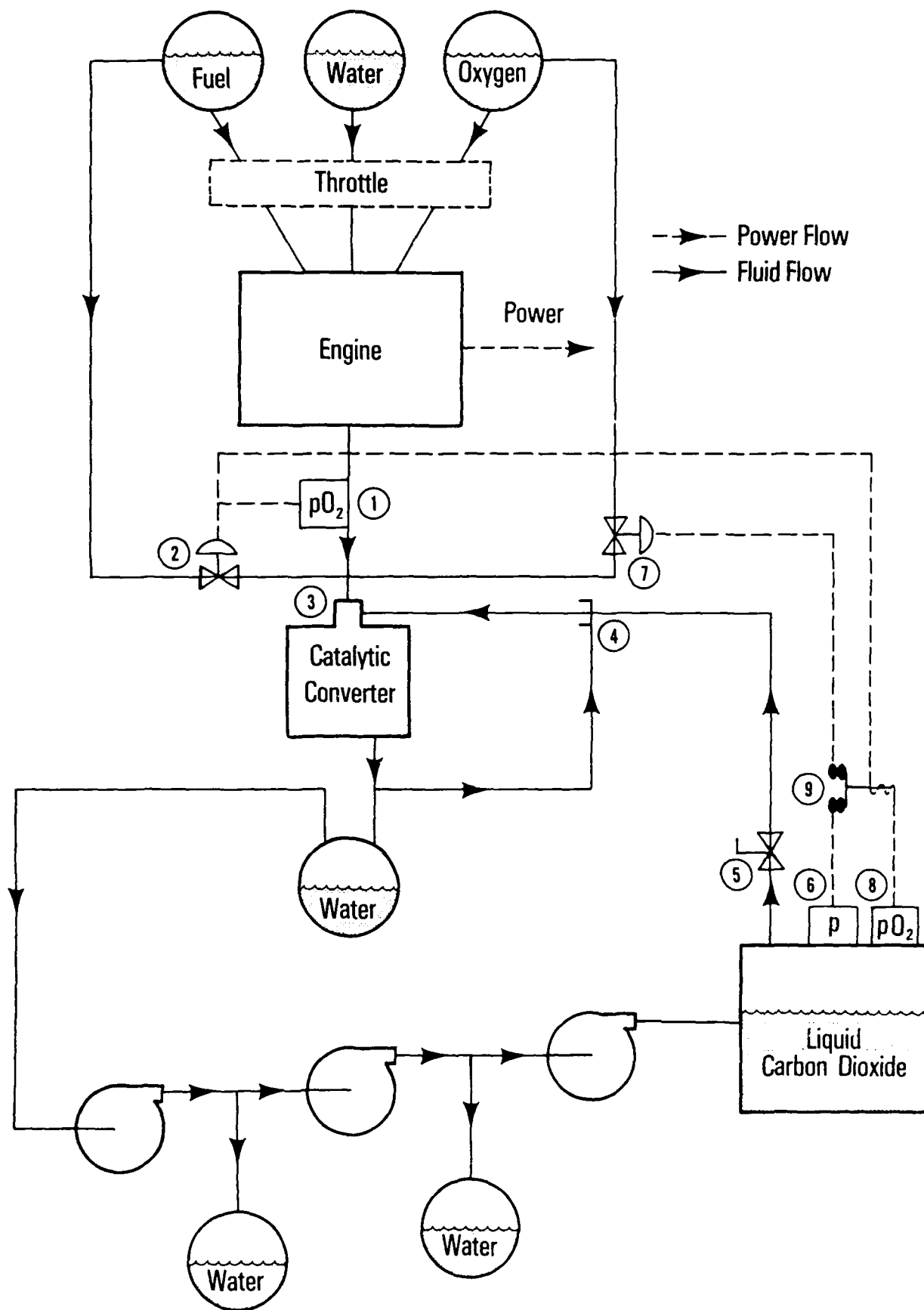
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Figure 3.

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Key for Figure 3:

1. Partial pressure oxygen sensor and sender at engine exhaust.

2. Control valve to release fuel to catalytic converter if partial pressure oxygen in engine exhaust or storage tank is abnormally high.

3. Ejector driven by engine exhaust to help circulate exhaust gases more than once through catalytic converter before going to compressor.

4. Same as Item 3, but driven by gas bled from final storage tank. Composition of bled gas includes CO.

5. Metering valve to adjust bleed gas flow rate.

6. Storage tank pressure sensor and sender. Pressure indicated is saturation pressure of CO_2 plus partial pressure of CO. Increase of total pressure normally implies equal increase in partial pressure of CO and proportional increase of CO fraction. CO_2 pressure is set by temperature of storage tank.

7. Control valve to add oxygen to catalytic converter to react with CO in bleed gas when pressure of storage tank increases. Running engine lean would also serve this purpose.

8. Partial pressure oxygen sensor and sender at CO_2 storage tank. Purpose is to prevent further addition of oxygen to exhaust if oxygen inadvertently enters storage tank.

9. Normally closed relay to interrupt signal to oxygen control valve if oxygen partial pressure becomes abnormally high in storage tank.

CONCEPT EVALUATION, EXPERIMENTAL

To de   op an engine which ingests only propane, oxygen and water will require experimentation with starting and stopping procedures, propane-oxygen-water mixing, and redesign of some components. The prevention of an increase of the average temperature in the combustion chamber will also require some attention. To eliminate the possibility of burned valves, the Wankel engine may be the engine of choice for initial experiments.

A reasonable procedure for starting the engine is to gradually introduce increasing quantities of a slightly rich mixture while turning the rotor with a starter motor until the engine runs on its own. The first few unburned charges can be exhausted into the atmosphere until the catalytic converter system is developed; but eventually, in the closed system, the unburned slightly rich charges will have to be burned upstream of the compressor.

When the engine can be made to run reliably, operation should be at low power until experience is gained in identifying the problems that are unique to operation without a gaseous diluent. Measurements of power output vs fuel consumption and power output vs exhaust gas and cooling water temperatures should be taken. These tests should expose most of the more troublesome problems that will arise in the development of this engine concept. The development of the catalytic converter controls, the compressor system and the safe starting and stopping procedures for a closed system will then be appropriate.

When the basics of starting and continuous running at low power output have been achieved, it will be necessary to study the trade-off between maximizing the peak power production and maximizing the thermal efficiency of the engine. Reasonable constraints are that the peak temperatures of the hottest engine components and the maximum waste heat production rate should not be greater than when operating in air breathing mode. The difficulties are caused by the specific heats of water vapor which are relatively large compared to those of nitrogen. Also the other potential problems associated with water injection such as corrosion or quenching will have to be determined by experiment.

A preliminary analysis of the effect of water injection on thermal efficiency and peak power is presented in the appendix. The results indicate that the thermal efficiency of the engine on propane-oxygen-water will be only about 72 percent as large as the thermal efficiency on gasoline-air and the maximum power of the engine will be about 59% of maximum power on gasoline-air.

NET SPECIFIC FUEL CONSUMPTION

Condensation of water vapor is practical, even in the presense of gaseous diluent, but to produce nearly 1000 psi partial pressure of carbon

dioxide in the presence of a large fraction of gaseous diluent is impractical. Without gaseous diluent, however, pressurization and storage of carbon dioxide as a liquid is feasible.

Atmospheric operation of a Wankel engine can be expected to consume approximately 0.65 pounds of gasoline per hp-hr of shaft work produced or one pound of gasoline per 1.54 hp-hr of work. The results in the appendix indicate that on propane-oxygen-water one pound of propane will produce 1.14 hp-hr of work. There will also be a reduction in the effective performance because some of the work must be diverted to condensing the exhaust gas. The effective specific fuel consumption based on mission related work will necessarily increase.

To estimate the effective specific fuel consumption and thereby prove the feasibility of condensing the carbon dioxide, it is assumed that the exhaust gas will be compressed from 14.4 psi to 1300 psi in three stages, each with a compression ratio of 4.5. The carbon dioxide and water vapor produced by burning one pound of propane occupies 61.6 ft^3 before compression. From Figure 4, 97.5 hp per million ft^3 per 24 hours is required for one stage of compression. Therefore, approximately 0.44 hp-hr is required to compress the exhaust from one pound of propane to 1300 psi in three stages. The mission related work from a pound of propane is then 1.14-0.44 = 0.70 hp-hr which equals a net specific fuel consumption of 1.43 pounds of propane per hp-hr. This estimate is too large because it does not account for condensation of most of the water at low pressures. Also the final pressure will be considerably less than 1300 psi during operation in cold environments and perhaps even in warmer environments if the catalytic converter system is efficient. Countering the above, the 3 percent power loss at the interstage coolers and the power required to recompress converted carbon monoxide and the carbon dioxide bled from the storage tank are not accounted for because the efficiency of the proposed catalytic converter system is not known. These inaccuracies notwithstanding, an effective specific fuel consumption of 1.45 pounds/hp-hr is assumed to be a reasonable expectation.

CONCLUSION

The preliminary analyses of the performance of a Wankel engine which operates on oxygen, propane and water indicate that it will produce 0.70 hp-hr per pound of propane. This implies a penalty of about 120% extra weight of fuel and oxidizer above that required for operation with a gaseous diluent and chemical carbon dioxide scrubber. However, in the case of potassium hydroxide scrubber solution, the weight penalty of the solution is 470% of the weight of the fuel and oxidizer.

For sodium hydroxide the weight penalty of the granules is 140%. It is assumed that only a small quantity of water will be required for starting and that condensed water from the exhaust will be provided to the engine intake system during most of the operation.

on performance. The overall criteria for judging valve suitability are (1) adequacy of timing, (2) pressure drop, (3) reliability, and (4) replacement cost.

ACTUAL PERFORMANCE. The actual performance of a single-stage compressor is shown in Fig. 19 and of a two-stage compressor in Fig. 20. In each instance the independent variable is delivery pressure with the unit running at constant speed. The data of Fig. 21 are useful in estimating the power requirements of air and gas compressors. Compressors are greatly influenced as to capacity and horsepower by operation at altitude. Figures 22 and 23 illustrate this influence and give a means of correcting sea-level performance to the values obtaining at altitude.
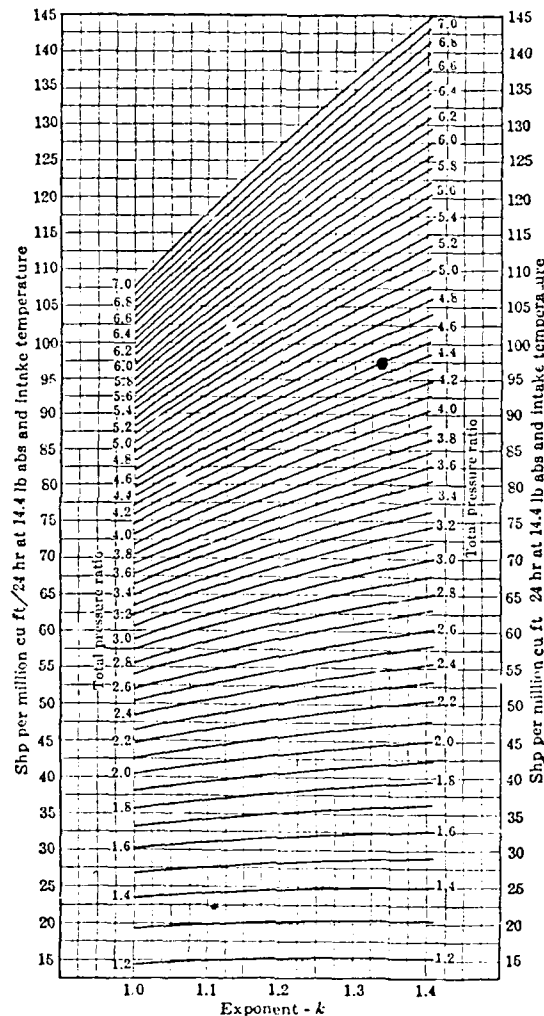
Fig. 21. Approximate horsepower to compress air or gas. Find exponent of gas from Table 1, p 1-40. If single stage, multiply actual capacity (in cu ft free gas per min) by 0.00144 to obtain capacity 1 million cu ft per 24 hr. Multiply this value by the ordinate obtained from the chart to obtain the total horsepower. If two stage, take square root of pressure ratio. Read horsepower from chart for this ratio; multiply by 2 (for two stages), and add 3% for cooler loss. (Adapted by permission of Worthington Pump and Machinery Corp.)

From Kent's Mechanical Engineer's Handbook

K = 1.33

Ratio = 4.5

Shp = 97.5

Figure 4

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Compared to the alternative weight penalty imposed by the scrubber chemicals, the extra consumables required for exhaust gas condensation are not really a penalty. In addition, the cost of the extra propane and oxygen is less than the cost of the chemical scrubber. The development of an engine to run on propane, oxygen and water and condense its own exhaust gases, all in a closed vessel, is recommended.

REFERENCE

1. Final Report Closed Cycle Engine Study, Contract N61331-82-R-0034
    Prepared by Perry Oceanographics, Inc. P. O. Box 10294
    Riveria Beach, FL 33404

APPENDIX

Estimate of specific fuel consumption and maximum power rating of an engine running on propane, oxygen and water compared to running on octane and air.

1. Compute the maximum temperature of combustion of an Otto cycle burning octane and air.

2. Compute the proportion of liquid water to be injected in propane and oxygen to produce the same temperature of combustion as in Item 1.

3. Compute the thermal efficiencies of the mixes in Item 1 and Item 2 in an Otto cycle.

4. Using the data from Item 3 and the known performance of a Wankel on gasoline and air (assume octane = gasoline) compute the expected actual specific fuel consumption for a Wankel on propane, oxygen and water by ratio.

5. Using the data from Item 3 and assuming that the waste heat removal capability of the engine limits the maximum power output, compute the maximum power percentage for an Otto engine running on propane-oxygen-water compared to octane-air.

(1.) For one mole octane w. stoichiometric air

$$C_8H_{18} + 12.5O_2 + xN_2 \rightarrow 8CO_2 + 9H_2O + xN_2$$
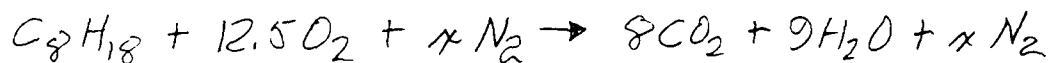
$Air = 79\% N_2, 21\% O_2 \therefore x = \frac{12.5}{21}(79) = 47.0$

Assume $k = \frac{C_v}{C_p}$ for octane $= 1.10$

$$\overline{k}_{reactants} = \frac{(1 \times 1.10) + (12.5 \times 1.38) + (47.0 \times 1.38)}{60.5} = 1.38$$

For isentropic compression $T_2 = \left(\frac{v_1}{v_2}\right)^{K-1} T_1$

For compression ratio of 8, $\frac{v_1}{v_2} = 8$

$T_1 =$ temperature at start of compression stroke
$T_2 =$ " " end of " "

Assume $T_1 = 60°F = 520°R$

$\therefore T_2 = 520(8)^{0.38} = 1146°R$

From Keenan & Kaye, p.95 @ 77°F = 537°R
   Enthalpy of comb. of octane $= 19,256$ BTU/lb
                                    (water as vapor)

$\therefore \Delta U_{comb @ const vol.} = \Delta H_y - \Delta N R T \qquad \Delta N = 64 - 60.5 = 3.5$

$$= \left(19,256 \frac{BTU}{lb}\right)\left(114.1 \frac{lb}{lb\,mole}\right) - (3.5)\left(\frac{1545}{778}\right)(537)$$

$$= 2,193,377 \text{ BTU}/lb\text{-mole @ }77°F$$

Assume $\Delta U_{77°F} = \Delta U_{1146°R}$

$\Delta U° = U_{prod\, T_f} - U_{prod\, T_i}$ See Lee-Sears p. 528
                                                   or Marks' p 4-54

$\therefore U_{prod\, T_f} = \Delta U° + U_{prod\, T_i}$ $T_i = 1146°R$

$U_{products}$ taken from Marks', p. 4-56, (See p. A-4)

$U_{prod,\,1146} = U_{prod,\,1100} + 0.46\left(U_{prod,\,1200} - U_{prod,\,1100}\right)$

$\therefore U_{prod\, T_f} = 2,193,377 + 8\left[4,778 + 0.46(958)\right] + 9\left[3,666 + 0.46(733)\right]$

$+ 47.0\left[2934 + 0.46(527)\right]$

$= 2,420,446 \dfrac{BTU}{lbmole\ octane}$

To find final temperature, use Marks p. 4-56
    Guess $5400°R$ and $5600°R$ (interpolated values) and
    interpolate for final temp.

Guess $T_f = 5600$

$U_{prod\, T_f} = 8(59,177) + 9(46,505) + 47(31,715)$
$= 2,382,566$

Guess $T_f = 5400$

$U_{prod\, T_f} = 8(56,569) + 9(44,293) + 47(30,337)$
$= 2,277,028$

$T_f = 5600 + \dfrac{2,420,466 - 2,382,566}{2,382,566 - 2,277,028}(200) = \underline{5672°R}$

4-56   THERMAL PROPERTIES OF SUBSTANCES AND THERMODYNAMICS

Table 46. Internal Energy of Gases
Btu per lb mol above 520°R

Temp. R	O_2	N_2	Air	CO_2	H_2O	H_2	CO	Ar
520	0	0	0	0	0	0	0	1,033
540	100	97	97	139	122	96	97	1,072
560	200	196	196	280	244	193	196	1,112
580	301	295	295	424	357	291	295	1,152
600	402	395	395	570	490	390	396	1,192
700	920	896	897	1,320	1,110	887	896	1,390
800	1,449	1,399	1,403	2,120	1,734	1,386	1,402	1,589
900	1,989	1,905	1,915	2,965	2,366	1,886	1,913	1,787
1000	2,539	2,416	2,431	3,852	3,009	2,387	2,430	1,986
1100	3,101	2,934	2,957	4,778	3,666	2,889	2,954	2,185
1200	3,675	3,461	3,492	5,736	4,399	3,393	3,485	2,383
1300	4,262	3,996	4,036	6,721	5,030	3,899	4,026	2,582
1400	4,861	4,539	4,587	7,731	5,740	4,406	4,580	2,780
1500	5,472	5,091	5,149	8,764	6,468	4,916	5,145	2,979
1600	6,092	5,652	5,720	9,819	7,212	5,429	5,720	3,178
1700	6,718	6,224	6,301	10,896	7,970	5,945	6,305	3,376
1800	7,349	6,805	6,889	11,993	8,741	6,464	6,899	3,575
1900	7,985	7,393	7,485	13,105	9,526	6,988	7,501	3,773
2000	8,629	7,989	8,087	14,230	10,327	7,517	8,109	3,972
2100	9,279	8,592	8,698	15,368	11,146	8,053	8,722	4,171
2200	9,934	9,203	9,314	16,518	11,983	8,597	9,339	4,369
2300	10,592	9,817	9,934	17,680	12,835	9,147	9,961	4,568
2400	11,252	10,435	10,558	18,852	13,700	9,703	10,588	4,766
2500	11,916	11,056	11,185	20,033	14,578	10,263	11,220	4,965
2600	12,584	11,682	11,817	21,222	15,469	10,827	11,857	5,164
2700	13,257	12,313	12,453	22,419	16,372	11,396	12,499	5,362
2800	13,937	12,949	13,095	23,624	17,288	11,970	13,144	5,561
2900	14,622	13,590	13,742	24,836	18,217	12,549	13,792	5,759
3000	15,309	14,236	14,394	26,055	19,160	13,133	14,443	5,958
3100	16,001	14,888	15,051	27,281	20,117	13,723	15,097	6,157
3200	16,693	15,543	15,710	28,513	21,086	14,319	15,754	6,355
3300	17,386	16,199	16,369	29,750	22,066	14,921	16,414	6,554
3400	18,080	16,855	17,030	30,991	23,057	15,529	17,078	6,752
3500	18,776	17,512	17,692	32,237	24,057	16,143	17,744	6,951
3600	19,475	18,171	18,356	33,487	25,067	16,762	18,412	7,150
3700	20,179	18,833	19,022	34,741	26,085	17,385	19,082	7,348
3800	20,887	19,496	19,691	35,998	27,110	18,011	19,755	7,547
3900	21,598	20,162	20,363	37,258	28,141	18,641	20,430	7,745
4000	22,314	20,830	21,037	38,522	29,178	19,274	21,107	7,944
4100	23,034	21,500	21,714	39,791	30,221	19,911	21,784	8,143
4200	23,757	22,172	22,393	41,064	31,270	20,552	22,462	8,341
4300	24,482	22,845	23,073	42,341	32,326	21,197	23,140	8,540
4400	25,209	23,519	23,755	43,622	33,389	21,845	23,819	8,738
4500	25,938	24,194	24,437	44,906	34,459	22,497	24,499	8,937
4600	26,668	24,869	25,120	46,193	35,535	23,154	25,179	9,136
4700	27,401	25,546	25,805	47,483	36,616	23,816	25,860	9,334
4800	28,136	26,224	26,491	48,775	37,701	24,480	26,542	9,533
4900	28,874	26,905	27,180	50,069	38,791	25,148	27,226	9,731
5000	29,616	27,589	27,872	51,365	39,885	25,819	27,912	9,930
5100	30,361	28,275	28,566	52,663	40,983	26,492	28,600	10,129
5200	31,108	28,961	29,262	53,963	42,084	27,166	29,289	10,327
5300	31,857	29,648	29,958	55,265	43,187	27,842	29,980	10,526
5400	32,607	30,337	30,655	56,569	44,293	28,519	30,674	10,724

$T =$ ~~5202~~ ~~31,715~~ ~~52,177~~ ~~26,505~~

Socker, C. Lichty, "Internal Combustion Engines," 1939, p. 482, derived from data given by Hershey, Eberhardt, and Hoetel, Trans. S.A.E. 31, 1936, p. 409.

$T \approx$ 5672   32,211   60,115   47,301

Combustion of Solid Fuels

For properties of solid fuels, heat values, etc., see Sec. 7.

Air Required for Combustion Let c, h, and o, denote, respectively, the parts of carbon, hydrogen, and oxygen in 1 lb of the fuel. Then the minimum amount of oxygen required for complete combustion is $2.67c + 8h - o$ lb, and the minimum quantity of air required is $a = (2.67c + 8h - o)/0.23 = 11.6[c - 3(h - o/8)]$ lb.

With air at 62°F and at atmospheric pressure, the minimum volume of air required is $v_m = 147[c + 3(h - o/8)]$ ft³. In

From Mark's Standard Handbook for Mechanical Engineers

∴ Theoretical flame temperature for stoichiometric octane and air burned at constant volume is 5672°R

② To burn propane-oxygen and add sufficient water to produce final temperature of 5672°R,

$$C_3H_8 + 5O_2 + xH_2O(\ell) \rightarrow 3CO_2 + 4H_2O + xH_2O(v)$$
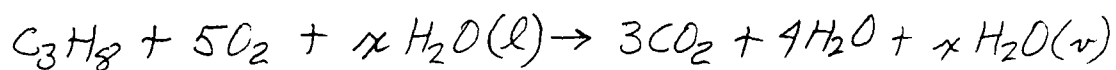
x is moles of water added per mole of propane

From Keenan & Kaye Gas Tables p. 95
Enthalpy of combustion of propane, water as vapor

$$= 19,929 \frac{BTU}{lb} \left(44.06 \frac{lb}{lb\,mole}\right) = 878,071 \frac{BTU}{lb\,mole}$$

$$\Delta U = \Delta H_p - \Delta NRT$$
$$= 878,071 - (1)\left(\frac{1545.1}{778}\right)(537)$$
$$= 877,004 \frac{BTU}{lb\text{-mole}}$$

$K_{propane} = 1.13$

assume injected water remains liquid during compression

$$\overline{K}_{reactants} = \frac{1(1.13) + 5(1.38)}{6} = 1.34$$

$$T_2 = 520(8)^{0.34} = 1054°R$$

$$U_{prod\,T_f} = \Delta U^\circ + U_{prod\,T_L} + U_{injected\,water} \quad T_L = T_2 = 1054°R$$

from Meeks p. 156
ref gas @ 520°R

$$= 877,004 + 3\left[3852 + 0.54(926)\right] + 4\left[3009 + 0.54(657)\right]$$
$$+ x\left(U_{fg}\,water\,ref\,vapor\,u=0\,@\,520°R\right)$$
$$= 903,515 + x\left[1003.5 + \frac{1.20}{11.63}(7.8)\right]\frac{BTU}{lb}\left(18\frac{lb}{lb\,mole}\right)$$

* from Keenan p. 34 Steam Tables

(a) $\qquad = 903,515 - 18,048x$

$U_{prod}{}_{TF} = 3(60,115) + (4+x)(47,301)$ from Marks p 4-56
$T_3 = T_F = 5672°R$

(b) $\qquad = 180,345 + 189,204 + 47,301x$

(a)=(b) $\quad 903,515 - 18,048x = 180,345 + 189,204 + 47,301x$

$$\underline{x = 8.17}$$

i.e. 8.17 moles (147 lbs) water must be injected per mole (44 lbs) of propane and per 5 moles (160 lbs) of oxygen consumed.

③ $Efficiency = \dfrac{\text{Expansion Work Done} - \text{Compression Work Required}}{\text{Heat Input}}$

$$W = \int_{V_i}^{V_f} p\,dV \qquad i = initial \qquad f = final$$

for isentropic compression or expansion $\quad p = \left(\dfrac{V_i}{V}\right)^K p_i$

$$\therefore W = \int_{V_i}^{V_f} \frac{V_i^K p_i}{V^K}\,dV = V_i^K p_i \left.\frac{V^{-K+1}}{-K+1}\right|_{V_i}^{V_f}$$

$$= \frac{V_i^K p_i}{1-K}\left[V_f^{1-K} - V_i^{1-K}\right] = \frac{V_i^K p_i}{1-K} V_i^{1-K}\left[\frac{V_f^{1-K}}{V_i^{1-K}} - \frac{V_i^{1-K}}{V_i^{1-K}}\right]$$

$$= \frac{V_i p_i}{1-K}\left[\left(\frac{V_f}{V_i}\right)^{1-K} - 1\right] = \frac{V_i p_i}{1-K}\left[\left(\frac{V_i}{V_f}\right)^{K-1} - 1\right]$$

$$V_i p_i = NRT_i \qquad\qquad \text{compression ratio} = 8$$

$$\therefore \text{Work of compression} = \frac{NRT_1}{1-K}\left[8^{K-1} - 1\right]$$

$$\text{Work of expansion} = \frac{NRT_3}{1-K}\left[\left(\frac{1}{8}\right)^{K-1} - 1\right]$$

T_1 is $520°R$ $\qquad\qquad T_3$ is $5672°R$

R is $1545.4 \ \dfrac{lb\ ft}{ft^2\ lb\text{-}mole\ °R}$

(a) For 1 lb mole octane + stoichiometric air $\quad K = 1.38$

$$W_{comp.} = \frac{(60.5)(1545.4)(520)}{(1 - 1.38)(778)}\left(8^{0.38} - 1\right) = -197,967 \text{ BTU}$$

For expansion after combustion $T_3 = 5672$

assume k for nitrogen $= 1.30$

$CO_2, H_2O = 1.20$

$$\overline{K} = \frac{8(1.20) + 9(1.20) + 47(1.30)}{64} = 1.27$$

$$W_{exp} = \frac{(64)(1545.4)(5672)}{(778)(1 - 1.27)}\left[\left(\frac{1}{8}\right)^{0.27} - 1\right] = 1,147,351 \text{ BTU}$$

$$\epsilon = \frac{W_{exp} + W_{comp}}{\Delta U} = \frac{1,147,351 - 197,967}{2,193,377} = 0.4328$$

$\therefore$ Theoretical efficiency on octane + air $= \underline{43.28\%}$

(b) For 1 lb mole propane + 5 lb mole O_2 + 8.17 mole water

Neglect volume of water in compression stroke.

$\overline{k} = 1.34$

$$W_{comp} = \frac{(6)(1545.4)(520)}{(1 - 1.34)(778)}\left(8^{0.34} - 1\right) = -18,736 \qquad \text{BTU}$$

For expansion $T_3 = 5672$, as above k for CO_2, H_2O is assumed to be 1.20 $\therefore$ $\overline{K} = 1.20$ also

$$W_{exp} = \frac{(15.17)(1545.4)(5672)}{(778)(1-1.20)}\left[\left(\tfrac{1}{8}\right)^{0.20} - 1\right] = 290,767 \text{ BTU}$$

$$\epsilon = \frac{W_{exp} + W_{comp}}{\Delta U} = \frac{290,767 - 18,736}{877,004} = 0.3102$$

∴ Theoretical efficiency on propane-oxygen-water = 31.02%

④ ∴ Expected actual specific fuel consumption on propane-O_2-H_2O

$$= \left(0.65 \text{ actual s.fc. on gasoline-air}\right)\left(\frac{0.4328}{0.3102} \text{ efficiency ratio}\right)\left(\frac{22,256}{19,929} \text{ heat content ratio}\right)$$

$$= \underline{0.876 \text{ lb.propane}/hp.-hr.}$$

⑤ Assume waste heat dissipation limits maximum power

For equal waste heat $\overset{rate}{\vee}$out, total heat $\overset{rate}{\vee}$in with propane-oxygen-water must be reduced by $\frac{(1-0.4328)}{(1-0.3102)} = 0.822$

Work $\overset{rate}{\vee}$produced with reduced heat $\overset{rate}{\vee}$input $=(0.822)(0.3102)$ of heat $\overset{rate}{\vee}$input with octane and air.

∴ Power produced with reduced heat $\overset{rate}{\vee}$input is $\frac{(0.822)(0.3102)}{0.4328}$
$= 0.589$ of heat input with octane and air.

I.E. Max. Power is $\underline{58.9\%}$ of air breather

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The development of a totally enclosed internal combustion engine is proposed. The engine will ingest propane, oxygen and water but no gaseous diluent. The elimination of the gaseous diluent permits the elimination of the scrubber chemicals previously required to remove the carbon dioxide produced by combustion. It is practical to liquefy the products of combustion, water vapor and carbon dioxide, and to store them as liquids if there is no gaseous diluent to be compressed during the liquefaction process.